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13. ABSTRACT (Maximum 200 words)

This Augmentation Award for Science and Engineering Research Training (AASERT) program supported the research of one graduate student (Pamela Greene) to carry out fundamental investigations of semiconductor lasers that make use of circular, two-dimensional Bragg gratings to define novel semiconductor laser microresonators. Such a laser can be described as a circularly symmetric, surface-emitting, distributed-feedback (DFB) semiconductor laser. Under ideal conditions, the spatial mode of the laser (within the waveguide) consists of a combination of radially inward- and outward-going circular waves coupled by the circular Bragg grating. The grating period is chosen to satisfy the second-order Bragg condition for back-reflection, so the grating in addition couples the circulating circular waves to the radiation field propagating normal to the mean surface (transverse cavity). The combined theoretical and experimental research examined the properties of the Bessel-Gauss beams emitted by these lasers and the details of transverse-mode selection in these two-dimensional lasers.

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Final Progress Report

Two-Dimensional Bragg-Microcavity Lasers

(DAAH 04-96-1-0147)

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The above-named award was made under the Augmentation Awards for Science and Engineering Research Training (AASERT) Program. As such, the award provided support for graduate student Pamela L. Greene (B.S., Rice University, double major in Electrical Engineering and French Literature). The basic objective of the award was successful, in that Pamela Greene completed her Ph.D. in Optics at the University of Rochester in May, 2000, under the supervision of Professor Dennis G. Hall. Dr. Greene, whose thesis carries the title "Radiation from Circular-Grating Distributed Feedback Lasers," recently moved with her husband (an electrical engineer) to California, where she works for Delta Tao Software, Inc. and does private consulting as a side venture.

Dr. Greene's AASERT-supported thesis research focused on fundamental investigations of semiconductor lasers that make use of two-dimensional, circular Bragg gratings to define novel semiconductor laser microresonators. Such lasers have come to be called concentric-circle-grating, surface-emitting (CCGSE) semiconductor lasers. Prior to Dr. Greene's thesis research, Prof. Hall's research group had already demonstrated fundamental-mode operation of CCGSE semiconductor lasers. Using circular gratings fabricated by electron-beam lithography (period = 0.25 μm) on AlGaAs/GaAs quantum-well lasers grown by molecular beam epitaxy (MBE), Prof. Hall and his students demonstrated a CCGSE semiconductor laser that emits a spectrally narrow (full-width at half-maximum of less than 0.1 nm), low-divergence (full angle less than one degree) beam with a circular cross-section. [1] One of the more interesting and unanticipated features of CCGSE lasers is the polarization of the output beam from those lasers. The laser emits what can be called an azimuthally polarized Gaussian beam, for which the transverse electric field is oriented tangent to circles centered on the beam's optical axis. [2]

Dr. Greene's research produced fundamental results in three areas. First, she investigated and defined the propagation characteristics of the above-mentioned azimuthally polarized Gaussian beams, examining free-space propagation and diffraction involving apertures and lenses. [3] She later extended that work to include the behavior of the (then) newly discovered set of vector Bessel-Gauss beams [4], of which the azimuthally polarized beam is only one member [5]. Second, she collaborated with fellow graduate student Craig Olson to demonstrate and report higher-order transverse-mode operation of CCGSE lasers. [6] Third, Dr. Greene carried out a sophisticated analysis of the impact radiation loss has on transverse-mode selection within the CCGSE laser. [7,8] The act of emitting a beam constitutes a loss mechanism that modifies the gain profile within the laser to influence which transverse mode can oscillate. This is an

important point in the CCGSE laser, for which the cavity is oriented perpendicular to the direction of the emitted beam. Her research was very successful, as evidenced by the seven publications (listed below) that have emerged so far from her thesis activities.

List of Publications

"Diffraction Characteristics of the Azimuthal Bessel-Gauss Beam," **Pamela L. Greene** and Dennis G. Hall, J. Opt. Soc. Am. A13, 962 (1996).

"Higher-Order Azimuthal Spatial Modes of Concentric-Circle-Grating Surface-Emitting Semiconductor Lasers," Craig Olson, **Pamela L. Greene**, Gary W. Wicks, Dennis G. Hall, and Steve Rishton, Appl. Phys. Lett. 72, 1284 (1998).

"Properties and Diffraction of Vector Bessel-Gauss Beams," **Pamela L. Greene** and Dennis G. Hall Journ. Opt. Soc. Am. A15, 3020 (1998).

"Focal Shift in Vector Beams," **Pamela L. Greene** and Dennis G. Hall, Optics Express 4, 411-419 (May 10, 1999). [Note: Article contains animation.]

"How to Create a Multimedia Article for Optics Express," **P. L. Greene**, Optics & Photonics News 11, 38-39 (January 2000). (Invited)

"Effects of Radiation on Circular-Grating DFB Lasers – I: Coupled-Mode Equations," **Pamela L. Greene** and Dennis G. Hall, **accepted** for publication in the IEEE Journal of Quantum Electronics (tentatively scheduled for publication in March, 2001).

"Effects of Radiation on Circular-Grating DFB Lasers – II: Device and Pump-Beam Parameters," **Pamela L. Greene** and Dennis G. Hall, **accepted** for publication in the IEEE Journal of Quantum Electronics (tentatively scheduled for publication in March, 2001).

In addition, Dr. Greene made a number of oral presentations at conferences, listed below.

Papers Presented at Conferences

"Fabrication and characterization of concentric-circle-grating distributed feedback semiconductor lasers," Craig Olson, Dennis G. Hall, and **Pamela Greene**, Annual meeting of the Optical Society of America, October 15, 1997.

"Radiation modes of concentric-circle-grating surface-emitting semiconductor lasers," **Pamela L. Greene** and Dennis G. Hall, Annual meeting of the Optical Society of America, October 15, 1997.

"Diffraction characteristics of vector Bessel-Gauss beams," **Pamela L. Greene** and Dennis G. Hall, presented at the Annual Meeting of the Optical Society of America, Baltimore, MD, October 7, 1998.

"Spiral-grating surface-emitting semiconductor lasers," Craig Olson, **Pamela L. Greene**, and Dennis G. Hall, presented at the Annual Meeting of the Optical Society of America, Baltimore, MD, October 8, 1998.

"Effects of radiation loss in concentric-circle-grating surface-emitting semiconductor lasers," **Pamela L. Greene** and Dennis G. Hall, presented at the Annual Meeting of the Optical Society of America, Baltimore, MD, October 8, 1998.

One of the above papers has an interesting story behind it. One of the properties of vector Bessel-Gauss beams [5] she analyzed was the focal shift of such beams near the geometric focus of the beam. After completing that piece of the work, she felt the best way to communicate the results was through animation, so she prepared a manuscript for submission to the new electronic journal *Optics Express*. The paper was accepted, and the article appeared in May, 1999. However, in the process of working with the *Optics Express* staff to sort out all of the format issues connected with making the animation process work, she developed something of a reputation for being able to manage the software issues. That reputation led to her being invited to write an article for *Optics & Photonics News* (a.k.a. *OPN*, the membership magazine of the Optical Society of America) describing how one goes about successfully jumping the various software hurdles. That article appeared in *OPN* in January, 2000.

Dr. Greene's analysis of the behavior of a radiating CCGSE laser is a very important one because it includes a determination of the lasing thresholds of the various transverse modes. Most analyses of DFB lasers (circular, or otherwise) neglect the effects of radiation. Because the CCGSE semiconductor laser is a two-dimensional structure, the transverse mode density is sufficiently high that the presence or absence of radiation is very important. Said another way, there are so many modes that, in principle, can oscillate in a CCGSE laser that one cannot obtain a good estimate of what will happen in a real structure unless one includes the effects of radiation.

In many ways, the CCGSE laser is an elegant device with a great deal of potential for the future, even though fabricating such devices poses a significant challenge for current technology. Nevertheless, with growing emphasis on two- and three-dimensional Bragg structures for a variety of optical applications and with growing emphasis on what have come to be called nanoscale science and engineering, fabrication technology is sure to advance at a brisk pace during the next few years. So if the CCGSE laser is a little ahead of its time right now, it will very likely receive renewed attention in the years ahead.

References

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3. "Diffraction Characteristics of the Azimuthal Bessel-Gauss Beam," Pamela L. Greene and Dennis G. Hall, J. Opt. Soc. Am. A13, 962 (1996).

4. "Vector Beam Solutions of Maxwell's Wave Equation," Dennis G. Hall, Opt. Lett. 21, 9 (1996).

5. "Properties and Diffraction of Vector Bessel-Gauss Beams," Pamela L. Greene and Dennis G. Hall Journ. Opt. Soc. Am. A15, 3020 (1998).

6. "Higher-Order Azimuthal Spatial Modes of Concentric-Circle-Grating Surface-Emitting Semiconductor Lasers," Craig Olson, Pamela L. Greene, Gary W. Wicks, Dennis G. Hall, and Steve Rishton, Appl. Phys. Lett. 72, 1284 (1998).

7. "Effects of Radiation on Circular-Grating DFB Lasers – I: Coupled-Mode Equations," Pamela L. Greene and Dennis G. Hall, accepted for publication in the IEEE Journal of Quantum Electronics (tentatively scheduled for publication in March, 2001).

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